HYDROGEN SPARK GAP FOR HIGH REPETITION RATES

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Abstract

The Pulsed Power Technology Branch at NAVSWC is investigating high-power switch technologies. In-house efforts have concentrated on spark-gap switches because of their high-voltage and high-current capabilities in single-shot devices and because of their simplicity and low cost. We have found that using hydrogen gas, with its high thermal diffusivity, allows an order-of-magnitude improvement in the recovery time (and, therefore, repetition rate) of an unblown spark-gap switch. Recovery of the switch can be made even faster by triggering the switch well below its self-break voltage, allowing voltage to be reapplied while the gas is still hot. Tests have shown that recovery times (to the operating voltage) can be reduced an order-of-magnitude when the gap is undervolted by approximately 50%. Recent tests have demonstrated 100-microsecond recovery of an undervolted hydrogen spark gap at voltages up to 120 kV, peak currents up to 170 kA, and energies up to 12 kJ. Plans are underway to test the switch to 500 kV.

Background

The Naval Surface Warfare Center has been studying the recovery of pressurized gas spark gaps to develop a compact, high-power, high-repetition-rate switch. Efforts have concentrated on spark gaps because of their high-voltage and high-current capabilities in single-shot devices[1]. The work has focused on improving the repetition rates of spark gaps without resorting to high gas flow. Voltage recovery information has generally been obtained using a two-pulse technique where the first pulse breaks down the gap and the second pulse determines the recovery. Recovery is considered to be the voltage that can be placed across the electrodes without initiating another spark.

We have experimentally shown that the recovery process for an overvolted spark gap occurs in two stages[2]. The first stage is the recovery of gas density, which will provide the gas with its static or D.C. holdoff voltage.[3] The second stage, which is much longer, is the recovery of the ability to be overvolted.[4] A typical recovery curve is shown in Figure 1. For a spark gap triggered near static self-break, only the first stage is important for the recovery of the main gap.

Improvements with High-Pressure Hydrogen

For gases such as air, nitrogen, argon, oxygen, and SF_6, typical recovery times are on the order of 10 milliseconds. The recovery is dominated by the cooling time of the hot channel formed by the spark. We have found that using hydrogen gas, with its high molecular speed and thermal diffusivity, allows the recovery time to be an order-of-magnitude faster, or about 1 millisecond. The recovery times of air and hydrogen are compared in Figure 2. Fast recovery time has been demonstrated with gap spacings from 0.1 mm to 1 cm at pressures from atmospheric up to 7 MPa (1,000 psig). High gas pressures and small gap spacings have the advantage of a shorter arc, which reduces inductance, resistance, and allows closer gas contact to metal surfaces. High density gas also increases heat capacity, increases the breakdown strength, improves turbulent cooling, and reduces statistical time. Hydrogen's low molecular weight allows fast channel expansion, so that turn-on time and gap losses are reduced.[5] High-pressure hydrogen allows the operation of a low-loss spark-gap switch with one millisecond between pulses and without gas flow.

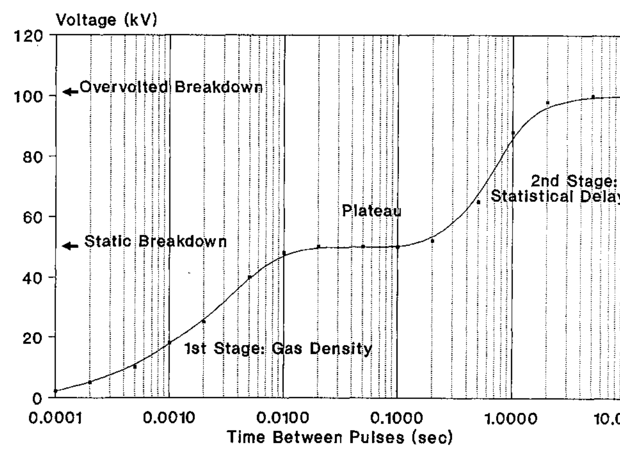

Figure 1. Two stages of overvolted spark-gap recovery. Charge-voltage risetime is 1 kV/ns in an air gap at 450 kPa (50 psig).

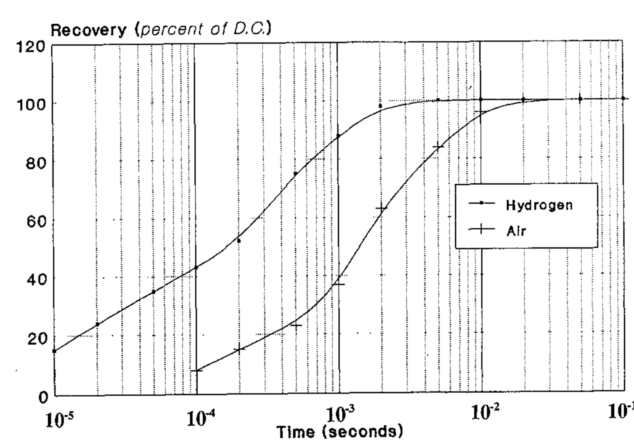

Figure 2. Recovery time of a high-pressure spark gap. Pressure is 1.4 MPa (200 psig) in a 2.5-mm gap.

Improvements by Undervolting the Gap

Recovery of a spark-gap switch can be made faster by triggering the switch well below static or self-breakdown voltage ("undervolting" the switch). For triggered gaps, the recovery-vs.-time plots for all the gases we have tested exhibit the profile shown

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14. ABSTRACT

The Pulsed Power Technology Branch at NAVSWC is investigating high-power switch technologies. Inhouse efforts have concentrated on spark-gap switches because of their high-voltage and high-current capabilities in single-shot devices and because of their simplicity and low cost. We have found that using hydrogen gas, with its high thermal diffusivity, allows an order-of-magnitude improvement in the recovery time (and, therefore, repetition rate) of an unblown spark-gap switch. Recovery of the switch can be made even faster by triggering the switch well below its self-break voltage, allowing voltage to be reapplied while the gas is still hot.

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in Figure 2, extending typically two orders-of-magnitude in time. The amount of time needed to recover half of the self-breakdown voltage is about one-tenth the time needed to recover the full self-breakdown voltage. This is due to the dependance of gas density (and, by Paschen's law, breakdown voltage) on temperature. Recovery time can be decreased by making the operating voltage of the switch significantly below self-break, allowing the operating voltage to be reapplied before the gas has returned to ambient temperature. The undervolting, in effect, allows the gap to operate at higher temperatures. The gas does not need to completely cool to prevent a spark from re-forming.

Tests with hydrogen in trigatron-type spark gaps have shown that recovery times (to the operating voltage) can be reduced an order-of-magnitude when the gap is undervolted by approximately 50%. Trigger pin spacings and electric fields are adjusted to launch simultaneous streamers toward both main electrodes. This allows maximum overvoltage with minimum misfires[6]. Trigger voltages are typically equal to the working voltage of the gap, although energies are much lower. 100-microsecond recovery has been demonstrated in an unblown spark gap using high-pressure hydrogen in a trigatron configuration.[7] Gap spacings and pressures were adjusted to self-break at twice the operating voltage. A single-shot trigger was used to initiate breakdown. Reapplication of the operating voltage without breakdown verified full recovery. A patent has been obtained for these techniques and the switch design[8].

Early Results

Tests were performed in 1987 at low energy (5 Joules) at 120 Kv peak voltage and 200 A peak current. In 1988, fast recovery was demonstrated at higher energies (200 Joules) using a 200-ns pulse-forming line (PFL). A 0.86-ohm water-glycol PFL was resonantly charged and was terminated with a matched liquid load.[9] The spark gap was triggered by a single-shot trigger at the peak of the first pulse. The voltage was reapplied in a 1-cos waveform (resonant charge) during the entire recovery period. The voltage waveform across the PFL is shown in Figure 3. The spark gap did not self-fire when the second voltage pulse was applied, showing full switch recovery to 60 kV (the PFL limit) in 100 microseconds. Current during the 200-ns pulse was 35 kA. Hydrogen gas pressure was up to 7 MPa (1,000 psi). Multiple pulses could not be tested because a rep-rated trigger was not available.

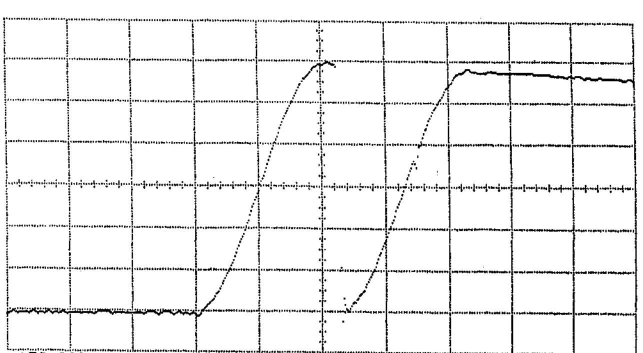

Figure 3. PFL voltage waveform showing full recovery at 60 kV and 35 kA. Vertical scale, 10 kV/div.; Horizontal scale 50 μs/div.

Switch Description

A drawing of a typical switch used in our experiments is shown in Figure 4. The pressure housing is 20 cm in diameter and made of stainless steel to withstand gas pressures up to 7 Mpa (1,000 psi). The insulators are machined from MACOR ceramic, and the electrodes and trigger pin are made from ELKONITE copper-tungsten. A quartz window is provided to view the gap, and silicon O-rings are used for sealing. Trigger-gap spacings are typically equal to half the main-gap spacings of about 6 mm. A typical breakdown field strength in pressurized hydrogen is 100 kV/cm at 680 kPa . As a safety precaution, hydrogen gas passes through excess-flow shut-off valves and flash arrestors. Triggering of the switch is typically done through isolation capacitors with a Maxwell 40295 100-kV trigger generator.

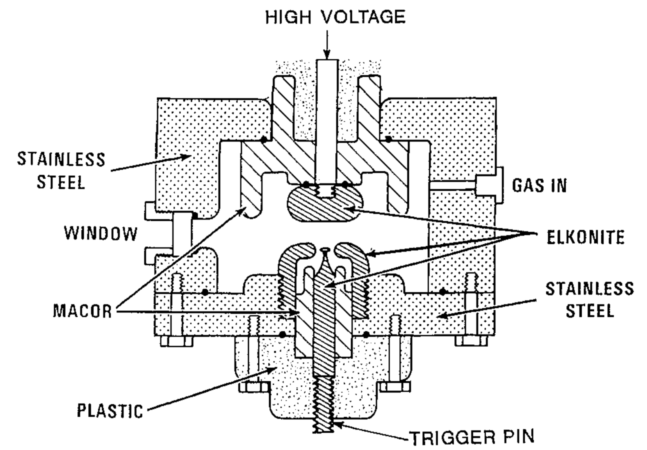

Figure 4. Cross-section of the high-pressure hydrogen spark gap. Housing diameter is 20 cm.

High Energy Tests

Switch testing was recently performed to see if hydrogen could handle high energies and maintain fast recovery times. Two 10-μF capacitor banks were connected via hydrogen switches to a common 0.1-ohm resistive-metal load. A schematic of the circuit is shown in Figure 5. Geometric inductance was about 600 nH. The capacitor banks were charged through high-voltage relays. When charged to 50 kV, the capacitor banks stored 12.5 kJ each. Separate single-shot triggers were used for each hydrogen switch. The resistive load damped the oscillations after about 1 cycle, giving a current pulse width of about 10 μs. Peak currents were 170 kA. Current through the load was measured with a T&M current-viewing resistor (CVR), and voltage was measured with a resistive probe. If the first spark gap did not recover before the second gap closed, the energy oscillated between capacitor banks rather than through the load, which was very obvious on the diagnostics. Figure 6 shows successful full recovery in 100 μs at 2.7 MPa (400 psi) at 50 kV. The top trace shows the current through the load from both pulses. The actual time between measurable current flows was less than 80 μs. The bottom trace indicates the voltage on the second capacitor bank. This voltage was transmitted with a NanoFast fiber-optic system which could not measure DC voltage. The output of the voltage trace therefore began at zero volts. There was no gas flow for these tests.

Gap spacings (electric fields) were critical in determining the degree of undervolting achievable and, therefore, the minimum recovery times as presented in Figure 2. Spark streamers should be created from the

trigger pin to both main electrodes simultaneously to allow operation at the maximum pressure. Jitter in the switch was insignificant on a microsecond time scale. These experiments showed that the recovery of an undervolted high-pressure hydrogen switch is a surprisingly weak function of the energy discharged through the switch. In fact, the recovery time varied little from millijoules to kilojoules of transferred energy. It appears that the higher energy transfer creates a larger, brighter, more turbulent and, perhaps, slightly hotter arc, which allows excess heat to be expelled in roughly the same time period. After hundreds of shots, erosion in hydrogen appeared similar to that of air gaps. The switch was also operated single-shot, with the resistive load shorted, at 260 kA peak current for an oscillating pulse 80 μs in duration.

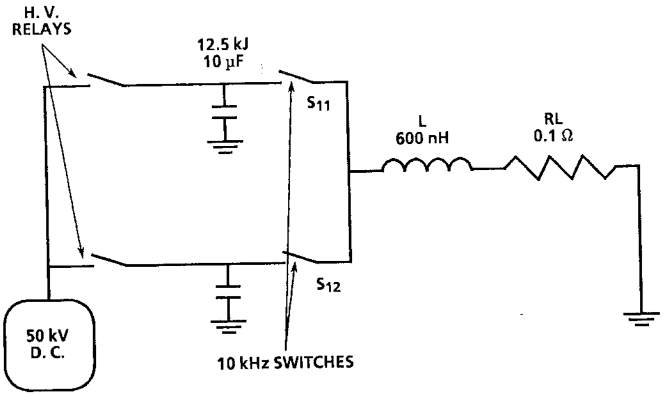

Figure 5. Simplified schematic of the high-energy experimental setup.

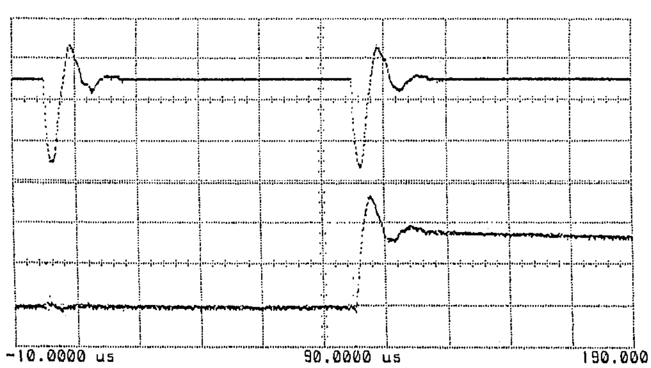

Figure 6. High-energy recovery in 100 μs at 2.7 MPa (400 psig) hydrogen after a 50-kV, 12.5-kJ pulse with 170 kA peak current.
Top trace (Ch-1): Current through resistive load at 80 kA/div.
Bottom trace (Ch-2): Voltage on second capacitor bank at 25 kV/div.
Time scale is 20 μs/div.

5-Pulse High-Voltage Tests

We are currently testing the hydrogen switch technology at high voltages. A 5-pulse system operating at 42 kV will be used to drive a step-up transformer to 500 kV. The transformer will charge a capacitor stack which will be discharged in a 5-pulse burst by a single, fast-recovery hydrogen switch. The purpose of these tests is to demonstrate that a fast-recovery hydrogen switch can operate at voltages of at least 500 kV while maintaining fast recovery in multiple-pulse bursts.

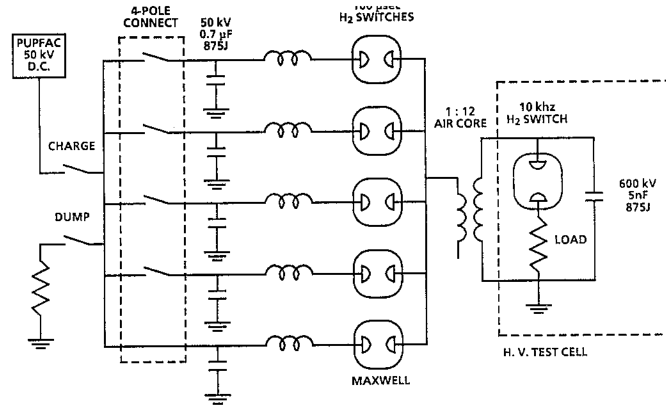

Figure 7. Schematic of the high-voltage 5-pulse test setup.

Low-Voltage Section

A schematic of the experiment is shown in Figure 7. Each primary capacitor (0.7 μF) can be charged through high-voltage relays to 50 kV D.C. storing 875 Joules. Each capacitor is discharged through a fast-recovery hydrogen switch controlled by a single-shot trigger in a similar setup to the high-energy tests described previously. Since all switches are connected to a common load, each switch must recover before the next one fires.

The low-voltage section of the 5-pulse system, up to the transformer, has been completed and produces a 5-pulse burst at charge voltages up to 50 kV. Each trigger has its own fiber-optic-controlled delay generator allowing bursts from 1 to 10 kHz. The system has produced 10-kHz bursts at 45 kV charge voltage into a 0.37-ohm resistive load. Figure 8 shows an example of the current through the load as measured by a CVR.

High-Voltage Section

The high-voltage section is currently being assembled. The transformer is a multi-turn-primary air-core pulse transformer with an output of 500 kV with a 42 kV input. Voltage risetime from the transformer is 12 μs to be compatible with charging a water capacitor while minimizing the primary current. The high-voltage section will be submersed in deionized water. The high-voltage capacitor is a series-stacked set of conventional capacitors discharged by a high-voltage pressurized hydrogen spark gap controlled by a multiple-pulse trigger. A folded resistive-metal load will be used to damp the oscillations in about a microsecond.

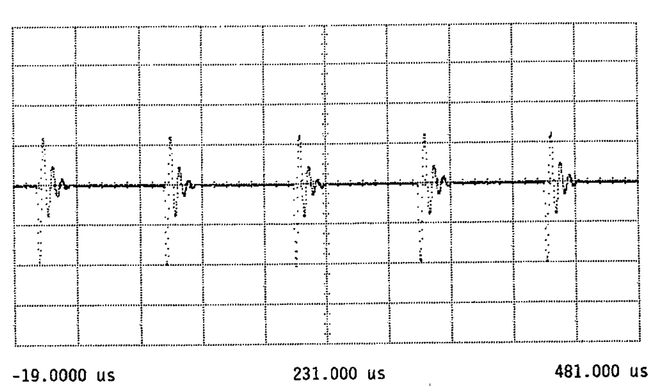

Figure 8. Current through a 0.375-Ω load showing full recovery of a 5-pulse burst at 10 kHz.
Hydrogen pressure was 2 MPa (275 psig)
Charge voltage was 45 kV (700 Joules/pulse)
10 kA/div (vert), 50 μs/div (horiz)

Trigger breakdown, main-gap breakdown, and timing for the five switches are all recorded on a logic analyzer using fiber-optic lines to measure light output from each switch window. Current in the primary and secondary are measured with fast current-viewing resistors. Voltage on the primary and secondary are measured with resistive probes.

High-voltage (>100kV) rep-rated triggering systems are currently under development. Several concepts are under investigation, including diode-isolated single-shot systems, hydrogen-switched Marx generators, and pulse transformers in series with hydrogen peaking gaps. We have recently demonstrated burst-mode capability at one kHz with a modified mini-Marx generator[10]. The 10-cm tube containing the 8-stage mini-Marx was operated at 775 kPa (100 psig) of hydrogen. The Marx was charged to 20 kV and burst-triggered with a hard-tube pulser. The charging waveform is shown in Figure 9a. The output gap was a two-electrode 1.5-cm gap operating at 775 kPa of hydrogen with a breakdown voltage of about 150 kV. The light emmited from the output gap is shown in Figure 9b.

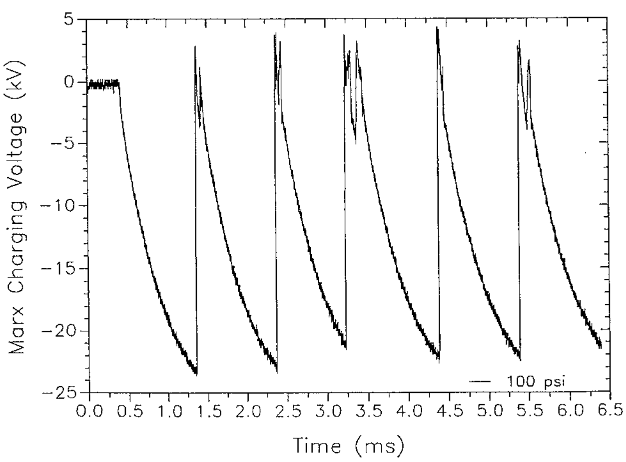

Figure 9a. Charging waveform into the 8-stage hydrogen mini-Marx.

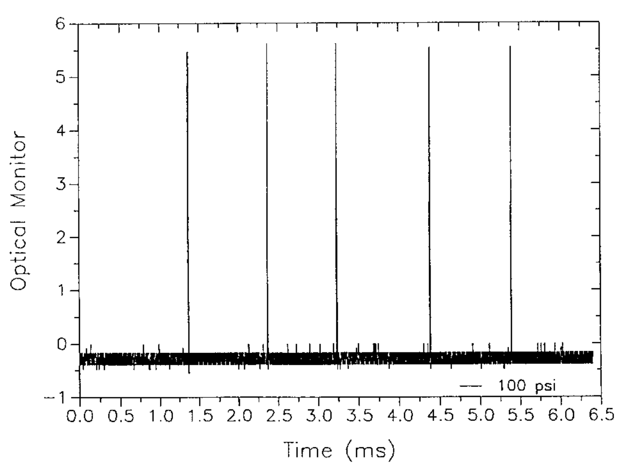

Figure 9b. Light output from the 1.5-cm output gap operating in 650 kPa hydrogen. Risetime is 2 ns, output voltage is 150 kV.

Several designs are under consideration for the high-voltage, multiple-pulse hydrogen switch. Tests will begin with modified versions of Sandia National Lab's V/N single-stage switch[11], and a switch developed for Sandia's TEMPO machine that uses multiple or cascaded gaps with resistive-wire field grading. Also under consideration is a reduced version of Sandia's RIMFIRE switch[12].

Summary

A high-power spark-gap switch capable of 100-μs recovery times can be constructed without gas flow using two techniques: high-pressure hydrogen gas, and triggering the main gap in a highly undervolted state. These techniques have been demonstrated to work at voltages up to 120 kV, peak currents of up to 170 kA, and energy transfers of up to 12.5 kJ. Tests are underway to test the concepts at 500 kV and for multiple-pulse bursts.

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